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Decoupling between fundamental frequency and energy envelope of neonate cries

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ABSTRACT

Background: The presence of decoupling, i.e. the absence of coupling between fundamental frequency variation and energy envelope during phonetic crying, and its extent, reflects the degree of maturation of the central nervous system.
Aim: We hereby wanted to assess the existence and extent of decoupling in term neonates (neurodevelopmental relevance) and whether an association between decoupling and clinical pain expression could be unveiled (clinical relevance).
Study design: To assess decoupling in healthy term neonates during procedural pain, newborns were videotaped and crying was recorded during venous blood sampling. Besides acoustic analysis, pain expression was quantified based on the Modified Behavioral Pain Scale (MBPS).
Subjects: 47 healthy term neonates underwent venous blood puncture at the 3rd day of life.
Outcome measures: Beside the MBPS score, the correlation coefficients were calculated between the fundamental frequency variation and energy envelope of the cries.
Results: Based on data collected in 47 healthy term neonates, correlation coefficients varied between 0.20 and 0.68. The degree of decoupling displayed extensive variability between the neonates and also in different cry bouts in a crying sequence within an individual neonate. A negative association was found between MBPS value and decoupling ($r^2 = -0.12$), the same as for the intra-subject variability although less extensive ($r^2 = -0.02$).
Conclusion: Decoupling only relates weakly with the amount of distress in 3 day old newborns, even though a great intra-subject variability is present. This study suggests that there is no evidence of extensive decoupling as the newborn still has to fully develop the control of larynx and abdominal muscles.

1. Introduction

One of the most important tools for infants to communicate is vocalization. In neonates, vocalization is mainly crying. Crying is considered to be a gradual signal, variable in duration, in intensity and whose meaning needs to be interpreted in its context [1]. The extent at which a newborn is stressed will also be reflected in its cry acoustics, causing different gradations in the cry signal, for example pitch or loudness. These gradations do not carry a specific message, but are more general, sudden and intense signals of stress.

From neurodevelopmental point of view, baby cries are the result of the interaction between control of different areas in the brain, respiratory control and vocal fold vibrations. At early stage, it is believed that a cry is the result of respiratory action and the effect of air going through a pipe, causing the vocal folds to vibrate, resulting in a cry bout [2], this is the vocalization produced during one expiration. The more the neural system matures, the more laryngeal control can be exerted resulting in manipulation and modulation of the cry signal, but observations on maturational aspects of the cry signal are limited and conflicting [3,4]. The development of the central neural system has been linked with the extent of vocalization control [4]. Based on the cry production model of Golub described in the work of Moller and Schonweiler [2] and Barr et al. [5], decoupling between variations in fundamental frequency and energy envelope during crying indicates cortical control. Decoupling is referred to as the absence of coupling between fundamental frequency variation and energy envelope during phonetic crying. In this cry model, cry production

Abbreviations: AR, auto-regressive; DAN, Douleur Aigue du Nouveau-Né; F0, fundamental frequency; EE, energy envelope; MBPS, Modified Behavioural Pain Scale; RMS, Root Mean Square.

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is controlled by a three level processor structure, in which the lower level can be separated into the subglottal, glottal and supraglottal cry production areas. The mid-processor is involved in physiological inputs like pain, blood levels and respiratory constraints, while the feedback processes are part of the upper-processor level, especially auditory feedback.

Besides crying, the response in which a newborn reacts on an external impulse like pain can also be quantified with validated clinical scoring systems. Such clinical scoring systems are often multimodal and not only include scoring of the body movements, but also acoustic features of the cry signal [6–9]. Within a predefined context like pain, analysis of crying characteristics might therefore provide additional information [3,10].

Bellieni et al. were able to document that newborns with a higher DAN (Douleur Aigue du Nouveau-né) score during venous blood sampling (heel lancing) also had a higher fundamental frequency and a correlation was found between the pain intensity (DAN score) and the normalized Root Mean Square value (RMS) [3]. The observation that the normalized RMS value increases with the DAN score indicates that the stationary character of the overall cry intensity increases with increasing pain. This can be interpreted as the energy envelope showing little variations during a cry bout with increasing pain. Facchini et al. looked to the relation between the DAN score and the occurrence of noise patterns in the sound spectrograms [10]. These noise patterns were chaotic and showed discontinuous parts in the crying signal, caused by a highly turbulent flow in the larynx. Results indicated that newborns with a higher DAN score showed more noise patterns.

To link cry characteristics with maturation, Wolf suggested that prior to one month of age infant cries are highly reflective and undifferentiated, but that shortly afterwards, cries progressively reflect various psycho-physiological states like hunger and pain [4]. In contrast, Bellieni et al. were able to document a correlation between cry features and DAN score in term neonates [3].

In the current study, we wanted to describe the dynamics within the baby cry and try to link these acoustic variables with clinical indicators of pain or stress expression in term neonates. We hereby wanted to investigate *(i)* whether decoupling can already be observed in term neonates (neurodevelopmental relevance), *(ii)* whether variability in decoupling could be quantified across the newborns and within the different cry bouts of one individual, and finally *(iii)* whether the degree of decoupling relates to clinical pain expression after venous blood sampling (clinical relevance).

2. Methods

Clinical pain expression and vocalization were simultaneously recorded in term neonates in whom a venous blood sampling was performed on the 3rd day of life for routine metabolic screening. Venepunctures were performed by a trained paediatrician. All babies were born in the University Hospital of Leuven (UZLeuven), in the period of July 2005 until March 2006. The study was approved by the Ethical Board of the University Hospitals and neonates were only included after written consent of the parents. In order to participate in this project, the baby had to fulfil the following inclusion criteria: minimal gestational age at least 37 weeks, no complications during pregnancy, a 1- and 5-minute APGAR score above 7, a minimal birth weight of 2.500 kg.

The vocalization produced by the newborn was recorded up to 3 min after the venous puncture, with a sampling frequency of 44.1 kHz at a distance of 0.5 m from the head of the baby. A cry from a baby consists of various cry bouts. Every cry bout is the result of the vibrations of the vocal folds during expiration. Due to the fact that the baby has to inspire, the cry bouts are separated by a pause. In infant cry analysis three types of vocalization are described [11]: phonation (voiced cries), hyperphonation (high pitched cries) and disphonation (turbulence and voiceless cry). Hyperphonation is often characterized by a higher fundamental frequency, while in disphonation a clear fundamental frequency and its harmonics are absent. In order to evaluate the relation between the variation of fundamental frequency and energy envelope, only manually selected voiced cry bouts (phonation) are used with a clear fundamental frequency.

Examples of cry bouts from a recorded crying signal are shown in Figs. 1 and 2. Signal analysis was done with Matlab R14 (Mathworks) and Adobe Audition 2.0 (Adobe). For every cry signal, consisting of various cry bouts, the relation between fundamental frequency and energy envelope is investigated. First the signals were filtered using a 6th order Butterworth filter with lower cut-off frequency of 200 Hz and upper cut of frequency of 2500 Hz, followed by a down sampling by a factor 8 of the signal to a sampling frequency of 5512 Hz. This allows us to investigate frequencies up to about 2700 Hz, under which the fundamental frequency is situated. The fundamental frequency was extracted by sliding a moving window (Hamming window of length 128 samples with 50% overlap) over the total cry bout. In every window, the fundamental frequency was derived, simultaneously with its energy envelope, using an autoregressive (AR) spectral estimation method [12]. The order of the AR model will influence the amount of peaks that are to be modelled. The higher the order, the more estimated the peaks. In our case, the model order was set to 20, based on the Akaike's Information Criterion (AIC). Fig. 3 illustrates the estimated AR spectrum on top of the Power Spectral Density plot (spectrum) for a clearly phonated cry signal. Using peak detection, the fundamental frequency is extracted for every window. The energy envelope is derived from taking the absolute value of the total cry bout after which it is filtered by a low pass 3rd butterworth filter at 40 Hz [13]. Afterwards the total energy envelope is windowed by the same window size as for the fundamental frequency extraction (128 samples) in which every window is represented by its mean to bring the energy envelope to the same sampling frequency as the fundamental frequency variation.

So, for every sliding window in a cry bout for which the AR spectrum is estimated, simultaneously the energy envelope was calculated. The result is shown in Fig. 1, in which the waveform is shown of a cry signal, together with its frequency variation and energy envelope (both normalized for visualization). In order to evaluate the degree of decoupling between the energy envelope and fundamental frequency (F0), correlation coefficient is calculated. The correlation coefficient $R(x, y)$ between signals x and y is related to the covariance C in the following way:

$$R(x, y) = \frac{\mathrm{cov}(\boldsymbol{x}, \boldsymbol{y})}{\sigma(x)\sigma(y)}$$

In this formulation cov(x,y) is the covariance between the vectors x and $\boldsymbol{y}$, respectively the energy envelope and the fundamental frequency variation. The standard deviations of x and y are represented as $\sigma(x)$ and $\sigma(y)$. The higher the degree of coupling, the higher the correlation coefficient R will be. A coupled and a decoupled cry bout are provided in respectively Figs. 1 and 2. In the decoupled cry bout (Fig. 2, $R = 0.12$), there is an initial rise in fundamental frequency after which it decreases, while in the coupled example (Fig. 1, $R = 0.77$) the energy envelope and fundamental frequency tend to follow each other. Since this correlation coefficient between energy envelope and fundamental frequency quantifies decoupling, it decreases as decoupling increases (i.e. a correlation coefficient $R = 0$ means total decoupling while a correlation coefficient $R = 1$ means total coupling). As decoupling/coupling in a cry bout is characterized by a wide range of possible transitions between both states, it is more likely to speak about coupling (decoupling) when the correlation coefficient goes towards 1 (0), instead of using a threshold value for the classification between the two classes.

Clinical pain expression was quantified based on the validated Modified Behavioural Pain Scale (MBPS) [14,15]. This is an easy applicable pain scale, based on visual and auditive scoring of facial

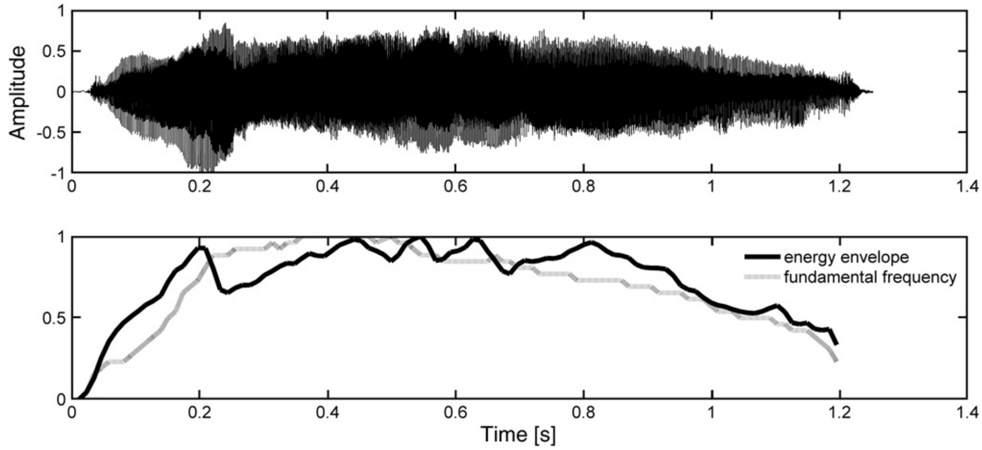

Fig. 1. Coupled cry bout showing its waveform with corresponding energy envelope and fundamental frequency variation (both normalized for visualization). The cross correlation coefficient R is 0.77.

expression, crying and body movements, each with a specific gradation. Summing the different sub scores results in a total score between 0 and 10 (Table 1). The MBPS was done by a dedicated evaluator trained for neonatal pain assessment based on the MBPS and was not involved in the venepuncture.

3. Results

47 healthy term neonates (20 boys, 27 girls), with a mean weight of 3.3 ± 0.4 kg were included, resulting in the recording of 1330 cry bouts. After selecting only those cry bouts with a clear phonation to enable the quantification of fundamental frequency variation, 1175 cry bouts remain. Mean MBPS was 7, and varied between 2 and 10. The mean number of cry bouts recorded in the 3-minute time interval was 28 (range 4–97). The mean gestational age was 39 weeks and 4 days (± 1 week and 2 days). Mean fundamental frequency was 547 (± 52) Hz. The highest fundamental frequency was observed at 843 Hz, the lowest at 200 Hz (Table 2).

3.1. Neurodevelopmental outcome

The degree of decoupling between fundamental frequency and energy envelope during a cry showed extensive inter-individual variability. In this cohort, the average correlation coefficients per subject calculated over all the cry bouts of the corresponding baby, recorded during the 3-minute test, varied between 0.20 and 0.68. A great variability between the degree of coupling/decoupling over all neonates has been observed, with a mean correlation coefficient of 0.43 ± 0.24.

When looking more in detail to the correlations of the cry bouts in a crying sequence, we also observed extensive intra-individual variability, expressed as the standard deviation over all cry bouts from one baby. This is illustrated in Fig. 4, where the correlation coefficients are shown for the 34 cry bouts recorded in one neonate. Although this baby displays a strong correlation between fundamental frequency and energy envelope up to 0.69, some cry bouts only have a low correlation coefficient (i.e. only 0.03) indicating higher degree of decoupling. In this case the mean correlation coefficient over all the 34 cry bouts is 0.29 ± 0.19. Over all the subjects, the standard deviation fluctuates between 0.069 and 0.342, indicating great intra-subject variability.

3.2. Clinical outcome

When evaluating the number of cries against the MBPS score, a weak and statistically not significant positive correlation was observed ($r^2 = 0.01$). It is not significant as the 95% confidence interval of the slope of the regression line, called β, holds 0 within its range, being -0.7 ± 113. Nor mean fundamental frequency nor standard deviation of the fundamental frequency during a crying sequence shows a relation with MBPS score (respectively $r^2 = -0.01$ and $r^2 = 0.03$). When plotting the MBPS values against the correlation

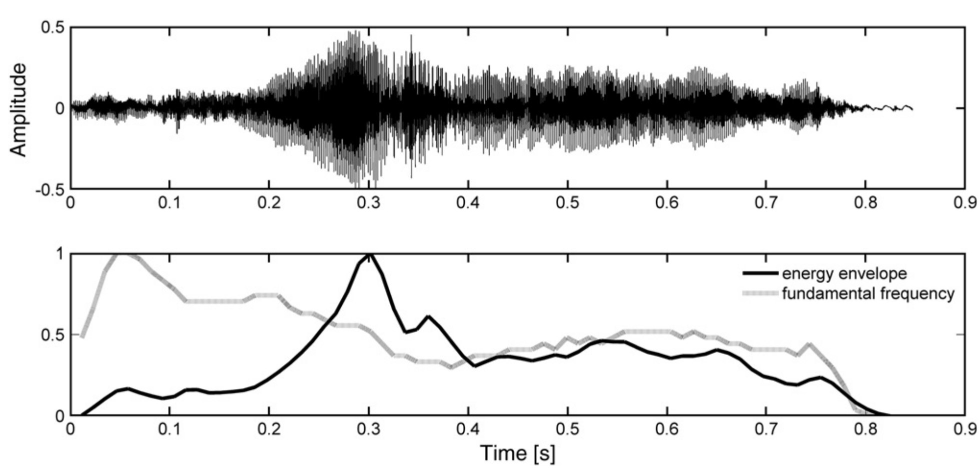

Fig. 2. Uncoupled cry bout showing its waveform with corresponding energy envelope and fundamental frequency variation (both normalized for visualization). The cross correlation coefficient R is 0.12.

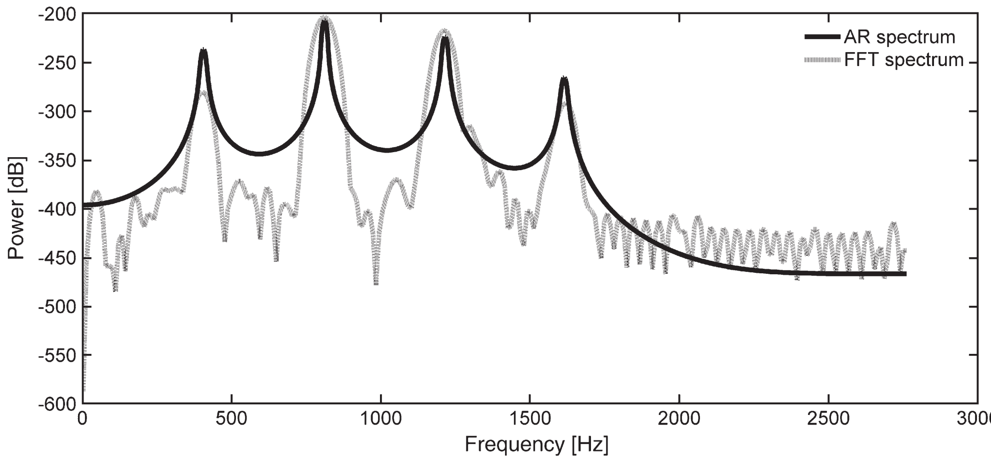

Fig. 3. AR model based and corresponding PSD spectrum from a phonated cry signal: the first peak is the fundamental frequency, the following peaks the harmonics.

coefficients (Fig. 5), no strong relation could be found, although significant ($\beta = -0.0144 \pm 0.0018$). The linear regression line has an r^2 of -0.12. The MBPS shows a weak, non significant relation with the individual standard deviations ($r^2 = -0.02$).

4. Discussion and conclusion

Based on crying characteristics collected during 47 procedures in term neonates, we were able to quantify decoupling and illustrate that it has an important inter- and intra-individual variability and that the degree of decoupling has a slight negative correlation with MBPS ($r^2 = -0.12$), while the intra-subject variability (defined as the standard deviation of the correlation coefficient quantifying the degree of decoupling) shows a less extensive negative relation with increasing MBPS value ($r^2 = 0.02$).

4.1. Neurodevelopmental aspects

The phenomenon of decoupling can be explained by the fact that the fundamental frequency and the amplitude envelope (energy envelope) are controlled by different muscles and nerves [16]. The fundamental frequency is controlled by airflow and the cricothyroid muscle, innervated by the external branch of the superior laryngeal nerve. This is a branch of the nervus vagus of which the motorneurons are located in the rostral part of the nucleus ambiguous in the brain stem. In contrast, the amplitude envelope mainly relates to abdominal wall muscles, which is innervated by the nerves T2–L3. The internal and external oblique muscles are activated before the m. transverses and rectus abdominis. While the oblique muscles and the m.

Table 1
The three scoring components of the MBPS are facial expression, cry and movements. The maximum possible MBPS value is 10.

	Score
Facial expression	
Definite positive expression	0
Neural expression	1
Slightly negative expression (i.e. grimace)	2
Definite negative expression (i.e. furrowed brows and eyes close tightly)	3
Cry	
Laughing or giggling	0
Not crying	1
Moaning, quiet vocalizing or gentle or whimpering cry	2
Full-lunged cry or sobbing	3
Full-lunged cry, clearly more than baseline	4
Movements	
Usual movements and activity	0
Resting and relaxed	1
Partial movement or attempt to avoid pain by withdrawing	2
Agitation with complex movements or rigidity	3

Table 2
Data overview.

Subject	Voiced cry	Total cry	MBPS	Mean corr coeff ± st. dev.	Mean FREQ ± st. dev.
1	39	66	8	0.494 ± 0.293	481 ± 33
2	63	71	9	0.277 ± 0.229	461 ± 40
3	28	30	3	0.480 ± 0.256	557 ± 28
4	37	60	5	0.515 ± 0.262	548 ± 28
5	7	8	4	0.468 ± 0.200	509 ± 28
6	58	64	7	0.394 ± 0.255	578 ± 31
7	27	33	10	0.472 ± 0.207	458 ± 26
8	18	19	9	0.355 ± 0.259	462 ± 27
9	6	6	3	0.680 ± 0.271	533 ± 26
10	41	42	10	0.406 ± 0.237	455 ± 37
11	12	13	8	0.306 ± 0.195	503 ± 29
12	33	34	10	0.381 ± 0.247	432 ± 194
13	19	21	8	0.311 ± 0.217	639 ± 24
14	36	48	10	0.430 ± 0.266	480 ± 26
15	34	37	6	0.290 ± 0.197	537 ± 25
16	14	15	3	0.486 ± 0.245	495 ± 25
17	11	11	9	0.448 ± 0.279	537 ± 36
18	4	4	8	0.202 ± 0.069	472 ± 35
19	8	12	8	0.540 ± 0.206	707 ± 32
20	19	23	6	0.337 ± 0.268	462 ± 32
21	16	26	8	0.565 ± 0.258	511 ± 22
22	11	11	8	0.377 ± 0.271	467 ± 25
23	25	29	10	0.369 ± 0.248	472 ± 27
24	11	12	9	0.330 ± 0.230	843 ± 47
25	36	40	10	0.548 ± 0.269	474 ± 26
26	8	8	4	0.470 ± 0.192	463 ± 31
27	30	31	8	0.424 ± 0.237	525 ± 44
28	15	17	4	0.377 ± 0.222	478 ± 21
29	28	29	8	0.508 ± 0.277	480 ± 22
30	8	8	7	0.434 ± 0.342	467 ± 31
31	70	74	8	0.363 ± 0.249	200 ± 79
32	91	97	7	0.422 ± 0.247	521 ± 27
33	33	36	10	0.270 ± 0.187	531 ± 70
34	37	37	3	0.596 ± 0.224	601 ± 41
35	8	8	7	0.319 ± 0.206	739 ± 36
36	22	24	7	0.451 ± 0.248	561 ± 27
37	21	22	5	0.601 ± 0.294	663 ± 42
38	9	10	8	0.420 ± 0.306	663 ± 58
39	13	13	10	0.485 ± 0.260	610 ± 28
40	10	12	8	0.517 ± 0.307	661 ± 80
41	16	17	4	0.469 ± 0.294	608 ± 32
42	27	28	8	0.552 ± 0.255	621 ± 76
43	37	37	8	0.444 ± 0.279	673 ± 32
44	29	30	10	0.391 ± 0.253	679 ± 37
45	30	34	10	0.389 ± 0.224	593 ± 32
46	6	6	2	0.445 ± 0.342	709 ± 36
47	14	17	8	0.583 ± 0.222	583 ± 29

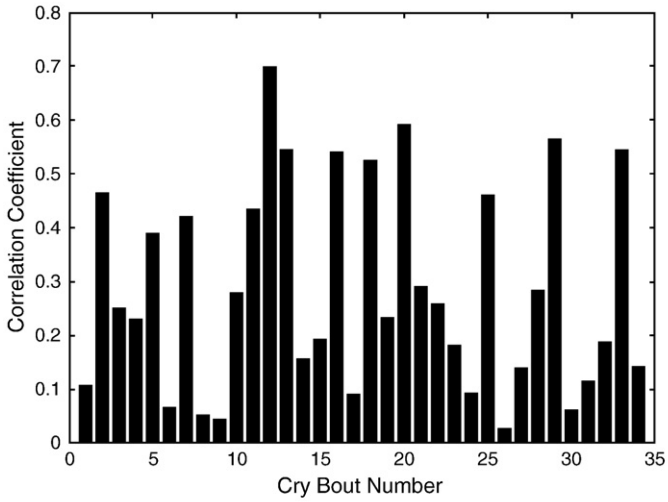

Fig. 4. Intra-subject variability is shown by the variation in correlation coefficient between different cry bouts of one crying signal. In this case the correlation varied between 0.03 and 0.70.

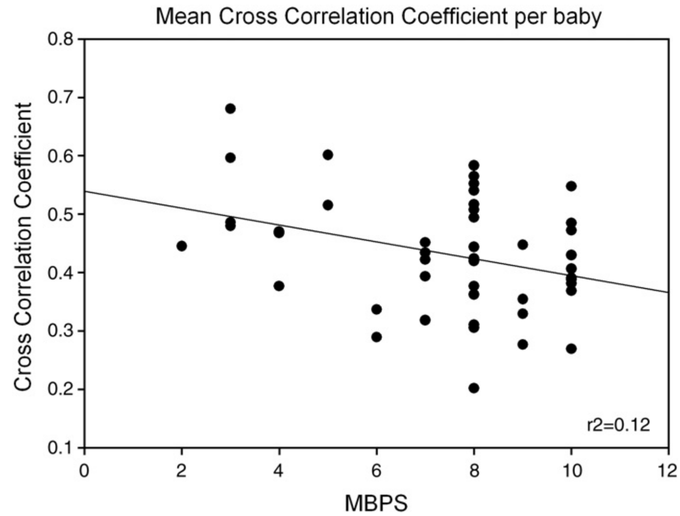

Fig. 5. MBPS values versus the mean correlation coefficient of all cry bouts for all the subjects.

transverses are well correlated in their activity with the amplitude envelope of phonation, there is only a loose relation between m. rectus activity and amplitude envelope [17].

Kent reports that the early divergence between speech and non-speech motor activities indicates that separate neural control systems are established in infancy [18]. Wermke et al. [19] documented a progressive increase in the ability of decoupling during crying in twins at age 8 –9 weeks, 15–17 weeks and 23 –24 weeks (postnatal age). Although the increase of the degree of decoupling has been observed, it was not clear to which extent three day old term neonates were able to decouple their energy envelope from their fundamental frequency. The results presented in this paper have quantified the extent of this decoupling. In total, the newborns showed an average correlation coefficient of 0.43, and the standard deviations of the correlation coefficients were up to 76% of their mean value, indicating high inter- and intra-subject variability. This suggests that there is no evidence of extensive controlled decoupling, probably as the newborn still has to fully develop the control of larynx and abdominal muscles. As mentioned earlier, the air expired from the lungs causes the vocal folds to vibrate, producing a fundamental frequency. According to the neural cry model discussed by Porter et al. [20], the modulation of this fundamental frequency is related to the dual innervation of the larynx by both parasympathetic and sympathetic input of the autonomic nervous system. Normal neurological development is characterized by a balance between these excitatory (sympathetic) and inhibitory (parasympathetic) forces. This whole process makes it unclear whether decoupling/coupling is clearly to be separated into cortical and subcortical processes, which might explain the high variability in the results.

4.2. Clinical aspects

When comparing the extent of clinical pain expression (MBPS score) with the degree of decoupling, a slight negative relation could be found. This is shown in Fig. 5 where a negative trend can be observed, although with low correlation ($r^2 = 0.12$). This might indicate that the degree of decoupling (and hence developmental status of the laryngeal control ability) in three day old newborns does not hold in great extent information about the stress reactivity expressed in MBPS values. In the past, other cry characteristics like fundamental frequency or oscillations have been linked with pain expression [3,10]. Bellieni et al. documented that the cry characteristics in neonates with a DAN score higher than 8 (higher reactivity) had a higher fundamental frequency [3]. The reason why this is not observed in our experiment is that Bellieni et al. used the heel-prick to evoke crying, a more severe blood sampling technique which leads to a higher excitation of the infant compared with our method. Fundamental frequency is also related to the listener's perception of a cry bout. Protopapas and Eimas [21] have shown that fundamental frequency and jitter are related to the listeners' perception, but results were inconclusive for the rise time (the time from the offset of phonation until the pitch reaches its maximum value). As the rise time is related to the variation of fundamental frequency in a cry bout, the conclusions might be similar for the degree of decoupling, but this is yet to be investigated as the quantification of decoupling also involves the variation in energy envelope.

In this study, it also has been shown that the intra-subject variability — expressed as the standard deviation of the degree of decoupling — shows a very weak negative relation with MBPS value ($r^2 = 0.02$). One might interpret the standard deviation within a subject with the consistency by which a cry bout it produced. As the ratio of the standard deviation of the correlation coefficients and the mean correlation coefficient is large in the studied subjects, it can be said that the cry bouts are produced with a low consistency.

Facchini et al. observed increased occurrence of noise patterns with high DAN scores, more specific with DAN scores between 8 and 10 [10]. These authors hereby postulated that noise patterns could be seen as distortions in the oscillating system caused by large variations in the vocal fold tension and tissue constants in distressed babies. This would imply that an increase in pain induces a chaotic transition in the vocal fold oscillation leading to noise patterns. As disphonation does not show a clear fundamental frequency, the AR method used in this study will not give a clear frequency contour. This is why the AR method for F0 estimation has been applied for cry phonations with clear fundamental frequency variations, and not for disphonation. The absolute values of the fundamental frequencies, obtained in this study via AR spectra, are in the same range as described in literature [3,10].

In conclusion, the method described in this paper is able to quantify decoupling and showed extensive inter- and intra-subject variability. Only a weak negative relation was found between decoupling and clinical reactivity (MBPS values) during procedural pain, as well as for the relation between the inter-subject variability and MBPS values, but less extensive. The results show that decoupling is not fully present in term neonates, and that the intensity of pain expression is to some extent related to the degree of decoupling. The consistency in which the cry bouts are produced shows a weak negative relation with the clinical reactivity. We conclude that decoupling is not implicitly linked to pain, suggesting that the method described in this paper might be relevant for neurodevelopmental rather than clinical assessment during venous blood sampling. For future research, it would be interesting to further describe the evolution in cry complexity and its covariates during the first few months of development, as the laryngeal muscles are still to be further developed in the following months after birth.

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